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Original Research

Evaluation of Centre of Resistance in Tooth with Different Levels of Bone: A Finite Element Method Study

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Abstract:

Background: The aim of this study is to evaluate the center of resistance (CRes) and rotation (CRot) in maxillary incisors with different levels of alveolar bone.

Subjects and Methods: In this study, the following steps were employed namely, (1) Preprocessing: The creation of geometric model, mesh generation, and boundary conditions. (2) Postprocessing: The tooth movement and determination of CRes and CRot.

Results: The results reveal that bone loss causes CRes movement toward the apex and its relative distance to the alveolar crest decreases at the same time. The study also suggested a decrease of the distance between CRes and CRot with increase of alveolar bone loss.

Conclusion: The study showed that the orthodontic forces should be kept as light as possible with a decrease in alveolar bone height. Applied force and moment magnitudes must be reduced in proportion to maintain physiologically tolerable movements with minimal damage to these supporting structures.

Key Words: Alveolar bone loss, center of resistance, center of rotation, finite element method

Introduction

Orthodontic tooth movement results from the application of forces to teeth. Tooth movement is primarily a periodontal ligament (PDL) phenomenon because it responds to the forces with a complex biologic reaction that ultimately results in the teeth moving through their supporting bone.

Finite element method (FEM) is an analytic tool developed in the 1940s for the use in civil and aerospace engineering. The term finite was the first coined and used by Clough in 1960. The FEM is a highly precise technique used to analyze structural stress.[1] FEM has many advantages over other methods highlighted by the ability to include heterogenecity of tooth material and irregularities of tooth contour. In orthodontics, FEM has been used successfully to model the application of forces to teeth. Many of the studies have concluded that FEM is a valuable tool and a non-invasive technique for analyzing the mechanical stress distribution within the periodontium during orthodontic force application.

With more adult patients seeking orthodontic treatment, there is an increased demand on clinicians for careful application of the force systems because of varying levels of alveolar bone height. To plan a tooth movement, the clinician must understand the force to be applied to the tooth and the stress distribution in and around the PDL and the cementum and it should be within the optimal force levels.[2]

Although bone resorption among orthodontic patients is not usual in most patients, certain factors should be considered in force system applications which include: (1) Force magnitude in relation to the amount of alveolar bone height, (2) modification of the moment/force (M/F) ratio to produce a certain form of tooth movement, and (3) the higher chances of tissue damage caused by greater amounts of tooth displacement.[3]

The aim of the study was to determine the center of resistance (CRes) and center of rotation (CRot) by applying a force of 1 N in upper central incisor tooth with an alveolar bone height of 13, 12, 10.5, 8, 6.5, and 5 mm using FEM. and to compare CRes and CRot in all the six models with various alveolar bone heights.

Subjects and Methods

Modeling of the tooth

The first step in finite element analysis is modeling. The quality of the analysis depends on the accuracy of the model. The maxillary central incisor was selected to simulate an outer morphology for FEM. Scanning procedure of the tooth was completed using computed tomography (CT) with a sliced thickness of 0.5 mm. The image section in CT is obtained in digital imaging and communication of medicine (DICOM). This obtained 2-D data was reconstructed to give a 3-D model using software called Pro/Engineer (parametric technology corporation, USA). The final model was completed by superimposing the prepared tooth model.

Boundary conditions, material properties, and applied load

After completion of the models, the assembly was then exported for analysis using ANSYS Workbench (ANSYS, Inc., USA) through a bidirectional understandable translator system called IGES. Once imported the software can do an automatic meshing and establish contacts with defined material properties. Isotropic material properties were applied for enamel, dentin, PDL, alveolar bone in the model in Table 1.

Six 3-D models of an upper central incisor were designed to conduct the research. Each model contained 8158-18204 nodes and 4092-9187 elements, depending on the degree of alveolar bone loss, which has been modeled in Table 2.

Tooth morphology was based on the Ash dental anatomy with minor modifications to get the best possible shape.

Structural components and the dimensions of the model

The 3-D brick isoparametric element with 8 nodes was chosen to make the models. Each model contained a tooth, its PDL, and both spongy and cortical bone.

Each model was divided into 13 layers. The first layer (most apical) acted as a base; the second one formed the subapical layer. In addition, 7 layers formed the root and 4 remaining ones made up the crown. There were different vertical heights at root layers: 1 mm at the cervical, 1.5 mm at the midroot, and 2.5 mm at the other layers. Designing such a meshwork with different element sizes allows having more accurate findings. Each layer was given 14 external nodes to enable acceptable modeling. The alveolar bone, as the sole difference of these models, was considered to have 13 (normal situation), 12, 10.5, 8, 6.5, and 5 mm heights.

The boundary condition was defined so that the models were restrained at their bases to avoid overall body motion.

Table 1: Mechanical properties for the structural elements.

Material	Young's modulus (N/mm²)	Poisson's ratio
Tooth	20300	0.30
PDM	0.667	0.49
Cancellous bone	15000	0.38
Cortical bone	34000	0.26

Table 2: Characteristics of the models used in this study.

Alveolar bone height (mm)	Bone loss (mm)	Nodes	Elements
13	0	18204	9187
12	1	13119	6598
10.5	2.5	12172	6115
8	5	10431	5227
6.5	6.5	9190	4602
5	8	8158	4092

A force of 1 N was applied to the labial surface of the tooth crown at each phase of the study, at 5.5 mm apical in respect to the incisal edge (This was presumed to be the location of the bracket). The point of force application was centered mesiodistally. Congruence of the line of action of the force with the long axis of the tooth avoids any rotation tendency at the models, due to the lack of any moment arm with respect to the tooth long axis.

There are 2 reliable criteria to study the behavior of tooth movement, CRes and CRot; consequently, finding the CRot of a simple tipping movement and the CRes of each model are 2 main goals of each phase of this study. Application of a point force of 1 N is suitable to find the CRot of the model. Evaluation of the displacement of the nodes at the root surface reveals that there are always 2 adjacent nodes at 2 different levels that show opposite directions of displacement. Using a simple geometric principle of right-angled triangles, the exact location of the CRot of the simple tipping movements was calculated at each model (with different alveolar bone heights).

As the second phase of the study, CRes was located. Different M/F ratios were applied and the M/F ratio which produces the bodily movement was identified by almost equal amounts of node displacements at different root levels. The CRes is derived from the M/F ratio which produced the bodily movement by using the formula $M = F \times d$, where d is the distance between the bracket slot and the CRes, F is the force which is kept constant throughout the study and M is the moment. Thus, the CRes for the models with different levels of alveolar bone height was identified by applying different M/F ratio to produce bodily movement.

Tooth, cortical, and cancellous bone can be considered rigid in relation to the PDL as a result of their greater differences in the Young's modulus. Thus, their deformations were calculated yet could be ignored. The present study is limited to the elastic phase of the materials used.

Results

The results of this analysis showed that when loaded by a force of 1 N, the center of resistance for a upper central incisor with normal alveolar bone height, i.e., 13 mm lies at 9.7 mm apical from the point of force application and the CRot lies at 5.28 mm from the root apex illustrated in Figure 1.

For 1 mm alveolar bone loss, i.e., for 12 mm alveolar bone height, the analysis showed that the center of resistance lies at 9.9 mm apical from the point of force application and the CRot lies at 5.06 mm from the root apex.

The analysis showed that for 2.5 mm alveolar bone loss, i.e., for 10.5 mm alveolar bone height the center of resistance lies at 10.3mm apical from the point of force application and the CRot lies at 4.64 mm from the root apex.

For 5 mm alveolar bone loss, i.e., for 8 mm alveolar bone height, the analysis showed that the center of resistance lies at 11.55 mm apical from the point of force application, and the CRot lies at 3.53 mm from the root apex.

For 6.5 mm alveolar bone loss, i.e., for 6.5 mm alveolar bone height the analysis showed that the center of resistance lies at 12.35 mm apical from the point of force application, and the CRot lies at 3.26 mm from the root apex.

For 8 mm alveolar bone loss, i.e., for 5 mm alveolar bone height, the analysis showed that the center of resistance lies at 13.18 mm apical from the point of force application, and the CRot lies at 2.9 mm from the root apex illustrated in Figure 2.

This study shows that the moment to force ratio required to produce bodily movement increases in association with alveolar bone loss. The results reveal that bone loss causes center of resistance movement toward the apex and its relative distance to the alveolar crest decreases at the same time. Greater amounts of displacements of incisal edge and apex were observed with increased alveolar bone loss for a constant applied force. Center of rotation of the tipping movement also shifted toward the apex with bone loss. This study showed that the center of resistance changes as a result of alterations in bone support. The study also suggested a decrease of the distance between CRes and CRot with increase of alveolar bone loss illustrated in Graphs 1 and 2.

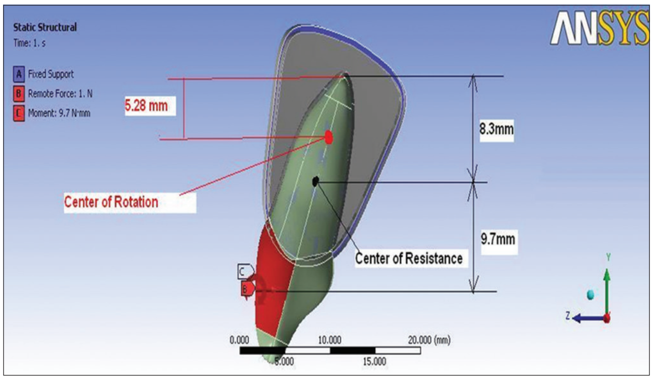


Figure 1: Location of CRes and CRot in normal alveolar bone height – 13mm.

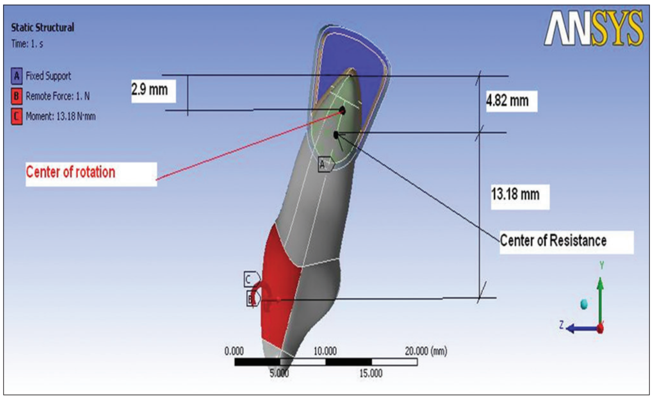


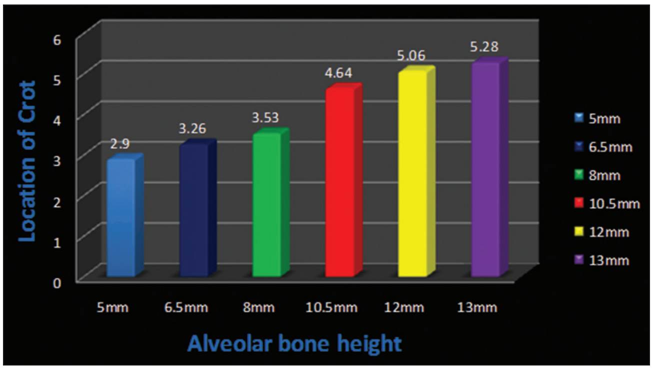
Figure 2: Location of CRes and CRot in alveolar bone height – 5mm(ie 8mm bone loss).

Discussion

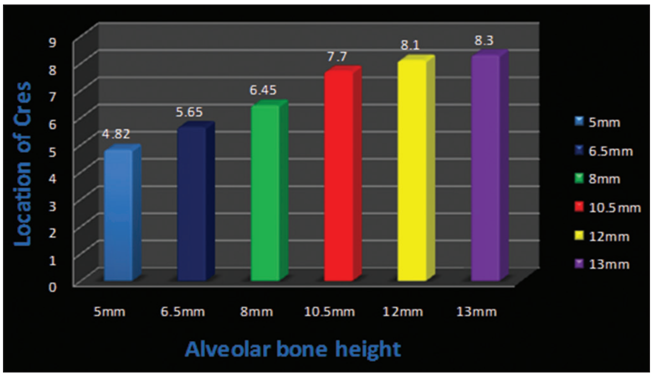
Orthodontic treatment involves controlled use of force systems to cause predetermined tooth movements. The principal changes resulting from such forces are seen within the dentoalveolar system. An optimal orthodontic force intends to induce a maximal cellular response with minimal adverse effects on supporting tissue.[4] During tooth movement, changes in the periodontium occur, depending on the magnitude, direction, and duration of force applied. The knowledge of the reactions of the supporting structures in orthodontic treatment is still incomplete because histologic techniques used today can provide only limited information.

Most orthodontic appliances deliver a relatively complicated set of forces and moments. The problems inherent in studying the response of a tooth subjected to a force system are much more complex and difficult to solve than those of simple measurement of the forces. Observations can be made on three levels to describe a tooth's response to forces: The clinical level, the cellular and biochemical level, and lastly the stress-strain level.

Perhaps the most important and the least understood level is the stress-strain level of activity in the PDL. The ability



Graph 1: Location of center of rotation with different bone levels.



Graph 2: Location of center of resistance with different bone levels.

to determine accurately the level of stress in different areas of the PDL may well offer the best means of correlating the application of force on a tooth with the tooth's response.[5] Currently, it is impossible to place strain gauges in the PDL to measure stress distributions; therefore, knowledge of stress phenomenon must depend on another approach. For example, a mathematical model of the tooth and surrounding structures can be constructed based on certain assumptions, and theoretic stress levels can be calculated from these models if the forces applied to the teeth are known. Unfortunately, these mathematical models are not better than the assumptions on which they are based. Therefore, better the mathematical model the more accurate will be the study.

Theoretical methods using engineering principles eliminate the need for direct experimental measurements. Photoelastic stress analysis is one of the methods and it can provide visual evidence of stress concentration areas within the model. Photoelastic method involves the construction of a model of the structure to be investigated from a photoelastic material. The model preparation for this method is arduous since it is critical that the model is of uniform thickness. Stress concentration area and magnitude of 3-D geometric shapes, which are subjected to mechanical load, can be calculated using mathematical methods. This calculation method cannot apply to complex structures, which are usually found in nature.

The purpose of the study was to evaluate the center of resistance in a tooth with different levels of alveolar bone when loaded by a force of 1 N. The Maxillary central incisor has been chosen for the study because during orthodontic treatment they are subjected to orthodontic forces for a prolonged period of time.

In this study, the 3-D FEM of a maxillary central incisor was created by various steps. The first step was the modeling. CT scan of a patient of central incisor was taken along with the alveolar bone. The scanned images were viewed with the software DICOM. The 2-D data obtained was reconstructed to give a 3-D model using software called pro/Engineer (parametric technology corporation, USA). After completion of the models, the assembly was exported for analysis using software called ANSYS (ANSYS, Inc., USA).

The maxillary central incisor model was created to represent the exact geometry of the root apex with morphology along with PDL. In the present study, the 3-D FEM had 22393 four nodes linear tetrahedral type and 87988 elements for enamel, dentin, and alveolar bone.

In the FEM study for tooth movement, Young's modulus and Poisson's ratio are the essential parameters, which are required as mathematical inputs for generating the FEM. The results are based on these inputs and any alteration would affect the outcome of results.

For any study of the stress pattern in the alveolar bone, the amount of force delivered plays a critical role. For this study, a force of 1N was applied to the labial surface of the tooth crown at 5.5 mm apical to the incisal edge. The point of force application was centered mesiodistally to avoid any rotational tendency.

Depending on the level of alveolar bone, the stress distribution in the FE model is represented by various color coding ranging from red to blue with red as maximum stress and blue as minimum stress, but the values for maximum and minimum stress areas will differ in each figure.

As the second phase of the study, CRes was located. Different M/F ratios were applied and the M/F ratio which produces the bodily movement was identified by almost equal amounts of node displacements at different root levels. The CRes is derived from the M/F ratio which produced the bodily movement by using the formula $M = F \times d$, where d is the distance between the bracket slot and the CRes, F is the force which is kept constant throughout the study and M is the moment. Thus, the CRes for the models with different levels of alveolar bone height was identified by applying different M/F ratio to produce bodily movement.

The analysis of the data provided by the various tooth movements was carried out. The results of this analysis showed that when loaded by a force of 1 N, the center of resistance for an upper central incisor with normal alveolar bone height, i.e., 13 mm lies at 9.7 mm apical from the point of force application and the CRot lies at 5.28 mm from the root apex.

For 1 mm alveolar bone loss, i.e., for 12 mm alveolar bone height the analysis showed that the center of resistance lies at 9.9 mm apical from the point of force application and the CRot lies at 5.06 mm from the root apex.

The analysis showed that for 2.5 mm alveolar bone loss, i.e., for 10.5 mm alveolar bone height the center of resistance lies at 10.3 mm apical from the point of force application and the CRot lies at 4.64 mm from the root apex.

For 5 mm alveolar bone loss, i.e., for 8 mm alveolar bone height the analysis showed that the center of resistance lies at 11.55 mm apical from the point of force application and the CRot lies at 3.53 mm from the root apex.

For 6.5 mm alveolar bone loss, i.e., for 6.5 mm alveolar bone height the analysis showed that the center of resistance lies at 12.35 mm apical from the point of force application and the CRot lies at 3.26 mm from the root apex.

For 8 mm alveolar bone loss, i.e., for 5 mm alveolar bone height the analysis showed that the center of resistance lies at

13.18 mm apical from the point of force application and the CRot lies at 2.9 mm from the root apex.

This study shows that the moment to force ratio required to produce bodily movement increases in association with alveolar bone loss. The results reveal that bone loss causes center of resistance movement toward the apex and its relative distance to the alveolar crest decreases at the same time. Greater amounts of displacements of incisal edge and apex were observed with increased alveolar bone loss for a constant applied force. CRot of the tipping movement also shifted toward the apex with bone loss. This study showed that the center of resistance changes as a result of alterations in bone support. The study also suggested a decrease of the distance between CRes and CRot, with increase of alveolar bone loss.

The study quantifies the effects of alveolar bone loss on CRot of simple tipping movements and CRes of the tooth. Initial tooth displacement increases with increased alveolar bone loss, which is in agreement with Tanne[6] Sia *et al.*[7] suggested that different heights of retraction forces could affect the direction of anterior tooth movement, his study stated that 3 mm of alveolar bone loss requires 20% of M/F ratio increment to maintain bodily movement, showing 17.35% of M/F ratio increment. Siatkowski *et al.*[8] reports an increase of 38% needed to produce bodily movement when 5 mm of marginal bone loss. Cobo *et al.*[9] state that with alveolar bone loss, CRes can be located above the alveolar bone crest. This study shows a decrease of CRes distance to alveolar crest, but the CRes was never found beyond the alveolar bone crest.

Early investigators indicated that multiple factors are involved for alveolar bone loss such as genetic and systemic factors, sex, tooth movement type, orthodontic force magnitude, duration and type of forces. They also categorized that these risk factors are patient related or treatment related.

The limitations of the study include some basic assumptions for the purpose of simulation. Although the mechanical behavior of the PDL is understood to be non-linearly elastic, many investigators assigned linear mechanical properties because of lack of scientific quantitative data. This lack of information is a source of error in computer simulations of orthodontic tooth movement.

Further, there is insufficient data available regarding the exact material properties of PDL since earlier investigators suggested that PDL should not be considered as an engineering material. Moreover, the cellular elements and tissue fluids could influence the property and behavior of the PDL, future studies may be required to clearly explain the exact material nature of PDL.

The clinical implication of the evaluation of center of resistance with alveolar bone loss is to keep the orthodontic forces as light as possible. The reduced supporting PDL area and volume result in ever higher amounts of displacements in supporting structures of affected teeth for a given level of force and moment magnitude. Applied force and moment magnitudes must be reduced in proportion to maintain physiologically tolerable movements with minimal damage to these supporting structures.

The future improvements in software and updated versions could help in the refinement of meshing process and creating a more accurate 3-D FE model.

Conclusion

The FEM analysis was undertaken to evaluate the center of resistance on the maxillary central incisor with different levels of alveolar bone when loaded by a force of 1 Newton. The maxillary central incisor has been chosen for the study because during orthodontic treatment they are subjected to orthodontic forces for prolonged period of time.

The conclusions of the study are:-

1. For normal alveolar bone height, the CRes was at 9.7 mm apical to the point of force application
2. For 1 mm alveolar bone loss, the CRes was at 9.9 mm
3. For 2.5 mm alveolar bone loss, the CRes was at 10.3 mm
4. For 5 mm alveolar bone loss, the CRes was at 11.55 mm
5. For 6.5 mm alveolar bone loss, the CRes was at 12.35 mm
6. For 8 mm alveolar bone loss, the CRes was at 13.18 mm.

The study showed that the orthodontic forces should be kept as light as possible with decrease in alveolar bone height. The reduced supporting PDL area and volume result in ever higher amounts of displacements in supporting structures of affected teeth for a given level of force and moment magnitude.[10] Applied force and moment magnitudes must be reduced in proportion to maintain physiologically tolerable movements with minimal damage to these supporting structures.

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